Estimation of ocean contribution at the MODIS near-infrared wavelengths along the east coast of the U.S.: Two case studies

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Received 8 March 2005; revised 31 May 2005; accepted 9 June 2005; published 13 July 2005.

[1] Atmospheric correction for the ocean color products derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) uses two near-infrared (NIR) bands centered at 748 and 869 nm. Ocean is usually assumed to be black at these two NIR wavelengths. For Case-2 and high productive Case-1 waters, however, ocean could have significant contributions in the NIR, leading to significant under-estimation of the MODIS-derived water-leaving radiances. This is often the case in coastal regions. In this paper, measurements from the MODIS Terra at the short wave infrared (SWIR) wavelengths (1240 and 1640 nm) are used to evaluate the ocean contributions at wavelengths 748 and 869 nm. The ocean is black in coastal regions in these SWIR bands due to much stronger water absorption. Studies of two MODIS granules off the east coast of the U.S. show that the ocean could have reflectance values of ~3.1% and ~1.8% at the top of atmosphere (TOA) for bands 748 and 869 nm in the Outer Banks, while these values are ~0.15% and ~0.1% in the Chesapeake Bay region. Thus, for the turbid waters, it is important to accurately account for the ocean contributions in the NIR bands for the atmospheric correction of ocean color remote sensing. **Citation:** Wang, M., and W. Shi (2005), Estimation of ocean contribution at the MODIS near-infrared wavelengths along the east coast of the U.S.: Two case studies, *Geophys. Res. Lett.*, *32*, L13606, doi:10.1029/2005GL022917.

1. Introduction

[2] To retrieve the ocean optical and biological properties from satellite measurements, the radiances that are contributed from the atmosphere and the ocean surface must be accurately removed. This is known as *atmospheric correction* [*Gordon*, 1997]. Typically, the top of the atmosphere (TOA) reflectance $\rho_t(\lambda)$ can be linearly partitioned into various physical contributions [*Gordon and Wang*, 1994]:

$$\rho_t(\lambda) = \rho_r(\lambda) + \rho_A(\lambda) + t(\lambda)\rho_{wc}(\lambda) + t(\lambda)\rho_w(\lambda), \qquad (1)$$

where $\rho_r(\lambda)$, $\rho_A(\lambda)$, $\rho_{wc}(\lambda)$, and $\rho_w(\lambda)$ are the reflectance contributions from the molecules (Rayleigh scattering), aerosols (including Rayleigh-aerosol interactions), ocean whitecaps, and ocean waters, respectively. $t(\lambda)$ is the atmospheric diffuse transmittance at the sensor viewing direction. The atmospheric correction algorithm for Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectroradiometer (MODIS), and Visible Infrared Imaging Radiometer Suite (VIIRS) uses aerosol information derived from sensor-measured two near-infrared (NIR) bands and then extrapolates it into visible wavelengths through evaluation of the aerosol parameter [*Gordon and Wang*, 1994]. To effect the atmospheric correction and derive aerosol properties, the ocean at the two NIR bands (748 and 869 nm for MODIS) is usually assumed to be black (i.e., $\rho_w(\lambda) = 0$). However, for the turbid ocean waters, ocean could have significant contributions at the NIR bands, leading to an over-estimation of aerosol $\rho_A(\lambda)$ contributions and an under-estimation of the derived water-leaving reflectance in the visible. It is important to account for the NIR ocean contributions in the atmospheric correction when the NIR $\rho_w(\lambda) > \sim 10^{-4}$ [*Siegel et al.*, 2000]. In this paper, we describe our efforts to derive the ocean contributions for the MODIS NIR bands (748 and 869 nm) using sensor-measured data at 1240 and 1640 nm. At the short wave infrared (SWIR) wavelengths (1240 and 1640 nm), water has more than one order stronger absorption than that at 869 nm band [*Hale and Querry*, 1973]. Therefore, ocean is still black even for the turbid waters. Note that both MODIS (Terra and Aqua) and VIIRS have SWIR bands, while SeaWiFS does not have measurements at wavelengths that are longer than 865 nm. We demonstrate through two MODIS case studies in the east U.S. coastal region that the water-leaving reflectances at the NIR bands have significant temporal and spatial variations, which are difficult to be estimated using bio-optical models. Examples of NIR ocean contributions from the Chesapeake Bay and Outer Banks regions are provided and discussed.

2. Ocean Contributions at the MODIS NIR and SWIR Bands

[3] Figure 1 provides an example of the ocean contributions at NIR and SWIR wavelengths from MODIS measurements. Figures 1a–1d are the TOA reflectance images in $[\rho_t(\lambda) - \rho_r(\lambda)]$ (Rayleigh-corrected reflectance) derived from the MODIS Terra measurements at wavelengths of 748, 869, 1240, and 1640 nm, respectively. The MODIS data were acquired on March 11, 2004 in the U.S. east coast region. Comparing with the open ocean regions (far away from coastal), Figures 1a and 1b show significant TOA Rayleigh-corrected reflectance contributions at 748 and 869 nm in the Outer Banks, while Figures 1c and 1d show consistently low reflectance values across the entire image (clear atmosphere). In the open ocean, the Rayleigh-corrected reflectance is usually within a range of 0.2%–

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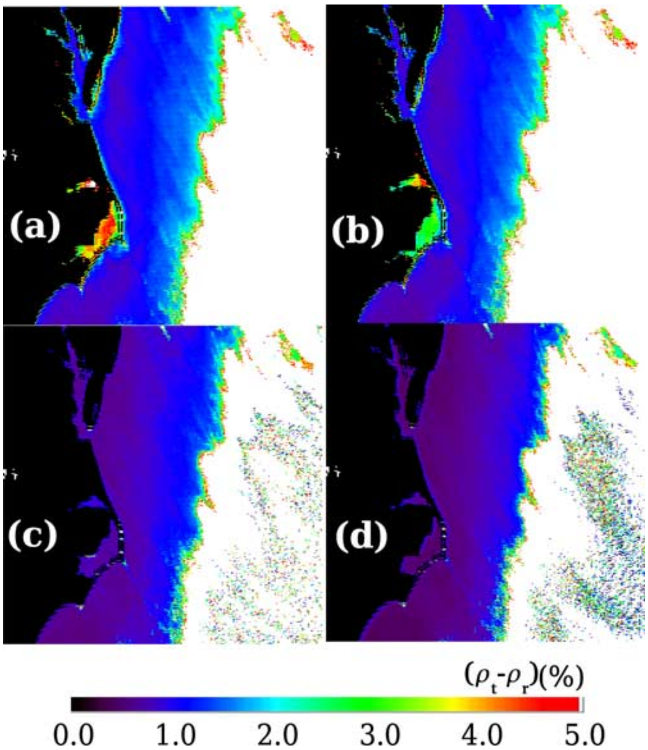

Figure 1. The TOA reflectance images in [$\rho_t(\lambda) - \rho_r(\lambda)$] derived from the MODIS Terra measurements on March 11, 2004 at wavelength (a) 748 nm, (b) 869 nm, (c) 1240 nm, and (d) 1640 nm.

0.5% in Figure 1 indicating that contributions are mostly from aerosol scattering. At the Outer Banks, however, the Rayleigh-corrected reflectance has extremely high values up to ~4%–5% at 748 nm and ~3%–4% at 869 nm. These excessive contributions at 748 and 869 nm are clearly from the ocean (not from the atmosphere) because the reflectance in the SWIR bands in the Outer Banks shows consistently low values as in the open ocean. The ocean signals in the SWIR are absorbed by the ocean water. Therefore, results in Figure 1 demonstrate that, for the turbid waters, ocean has significant contributions at the NIR (748 and 869 nm), while ocean is indeed black in the SWIR bands (1240 and 1640 nm) due to much stronger water absorption [*Hale and Querry*, 1973].

3. Derivation of the NIR Ocean Contributions

[4] In this section, we describe a procedure to derive the NIR ocean contributions using the MODIS SWIR bands. For this purpose, a vicarious calibration has been developed and applied to the two SWIR bands using the MODIS NIR data measured at the open ocean.

3.1. Vicarious Calibration for the SWIR Bands

[5] We have examined the MODIS measurements in the open ocean with very clear atmosphere and found some inconsistencies in deriving aerosol contributions between data from the NIR bands (748 and 869 nm) and the SWIR bands (1240 and 1640 nm). Figure 2 provides examples of these cases. Figures 2a and 2b compare the MODIS TOA reflectance $\rho_t(\lambda)$ between the simulated and measured values from the open ocean for the SWIR wavelengths of 1240 and 1640 nm, respectively, where the simulated value is estimated from 748 and 869 nm band observations. Figures 2a and 2b are results corresponding specifically to the sensor detector #6 and #5 for wavelengths of 1240 and 1640 nm, respectively. The MODIS data were acquired on April 16, 2004 from the east coast of the U.S. scene. In Figure 2, only open ocean data were used. From equation (1), by assuming the black ocean at the MODIS 748 and 869 nm (i.e., $\rho_w(\lambda) = 0$), aerosol optical properties (aerosol models and aerosol optical thickness at 869 nm) can be derived from the MODIS two NIR bands [*Gordon and Wang*, 1994]. The aerosol lookup tables for the SWIR bands were generated using the same 12 aerosol models for the SeaWiFS/MODIS ocean color data processing. With derived aerosol optical property data, aerosol contributions $\rho_A(\lambda)$ at the two MODIS SWIR bands can be estimated, and TOA reflectance $\rho_t(\lambda)$ at 1240 and 1640 nm can be computed. These computed $\rho_t(\lambda)$ values are compared to MODIS measurements as presented in Figure 2. In these computations, we have accounted for whitecap contributions from the NIR bands, while the whitecap reflectances in the SWIR (in the order of $\sim 10^{-5}$) are ignored due to much stronger water absorption [*Frouin et al.*, 1996].

[6] Results in Figure 2 show that a good linear relationship exists between the computed and MODIS-measured data for the two SWIR bands. The MODIS-measured TOA reflectance varies from ~0.4% to ~2.8% for 1240 nm, while the TOA $\rho_t(\lambda)$ changes from ~0.2% to ~2.3% at the 1640 nm band. However, comparing with computed values

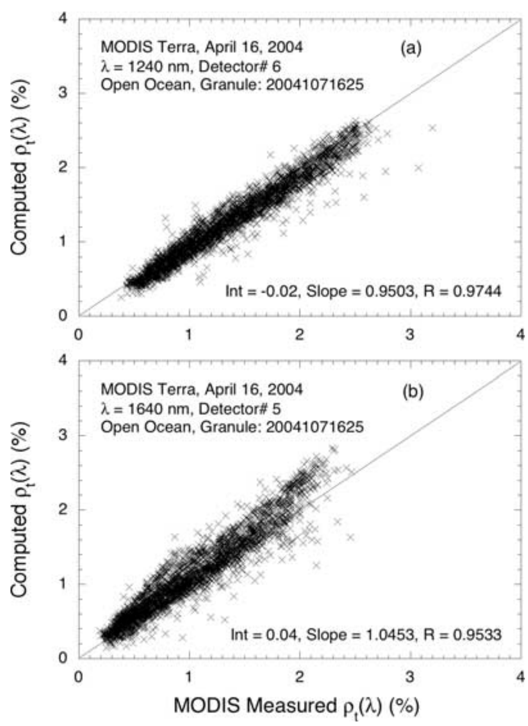

Figure 2. The MODIS-measured TOA reflectance $\rho_t(\lambda)$ from open ocean at wavelength (a) 1240 nm and (b) 1640 nm compared with the computed data that are derived from the MODIS measurements at 748 and 869 nm.

that were derived from the MODIS NIR data, the MODIS-measured $\rho_t(\lambda)$ has a slightly high bias at 1240 nm and slightly low bias at 1640 nm. These are indicated from a linear fit between the computed and measured data in Figure 2. Values of the linear fit computed for intercept (Int), slope (Slope), and correlation coefficient (R) are −0.02, 0.9503, and 0.9744 for the 1240 nm band and 0.04, 1.0453, and 0.9533 for the 1640 nm band, respectively. Since the MODIS SWIR bands are designed for land and atmosphere applications (bright signals), the designed sensor performance (signal-noise-ratio (SNR)) in these bands is poorer than those of the NIR bands (748 and 869 nm). Thus, we have carried out a vicarious calibration for the SWIR bands using the MODIS-measured data in the NIR over the open ocean where the ocean can be considered as black at these wavelengths. In effect, we have used the derived coefficients in the linear fit as in Figure 2 to re-compute the MODIS $\rho_t(\lambda)$ values such that the new fit will have intercept of 0 and slope of 1.

3.2. Procedure in Deriving the Ocean Contributions at NIR

[7] After performing a vicarious calibration to the MODIS two SWIR bands using the NIR data over open ocean, the MODIS 1240 and 1640 nm measurements can then be used to retrieve the aerosol optical properties through equation (1) with an assumption that both $\rho_{wc}(\lambda)$ and $\rho_w(\lambda) = 0$. The procedure for the aerosol retrievals and atmospheric correction is the same as for SeaWiFS and MODIS [*Gordon and Wang*, 1994], i.e., simply replacing the two NIR bands (748 and 869 nm) with the two SWIR bands (1240 and 1640 nm) for the data processing. In the same way as for the ocean color data processing, the derived aerosol optical properties in the SWIR are extrapolated into the NIR bands, and the TOA ocean contributions at 748 and 869 nm can be retrieved through equation (1), i.e.,

$$t(\lambda)\rho_w(\lambda) = \rho_t(\lambda) - \rho_r(\lambda) - \rho_A(\lambda) - t(\lambda)\rho_{wc}(\lambda). \qquad (2)$$

In the data processing, a new cloud-masking scheme that uses the MODIS 1640 nm band (instead of 869 nm) has been developed and implemented for the application of data retrievals. The cloud-masking using the SWIR bands performed much better than the NIR band, particularly in the coastal regions. In addition, the same SeaWiFS/MODIS sun glint masking that has been applied for the processing ocean color products has been implemented. The data processing procedures can be outlined as following:

[8] (a) From the MODIS Terra data, an open ocean region is selected for the vicarious calibration for the SWIR bands (1240 and 1640 nm) using the NIR measurements at 748 and 869 nm assuming $\rho_w(\lambda) = 0$.

[9] (b) With the vicariously calibrated $\rho_t(\lambda)$ at the MODIS two SWIR bands, the aerosol optical properties can be derived in the coastal regions through equation (1) using $\rho_w(\lambda) = 0$.

[10] (c) The derived aerosol optical properties in the SWIR are then extrapolated into the NIR bands and $\rho_A(\lambda)$ values can be estimated.

[11] (d) Finally, using the derived $\rho_A(\lambda)$, and with $\rho_r(\lambda)$ from the Rayleigh lookup tables and $t\rho_{wc}(\lambda)$ from model calculation using wind speed, the water-leaving reflectance at the TOA $t\rho_w(\lambda)$ can be computed according to equation (2) for the two MODIS NIR bands at 748 and 869 nm.

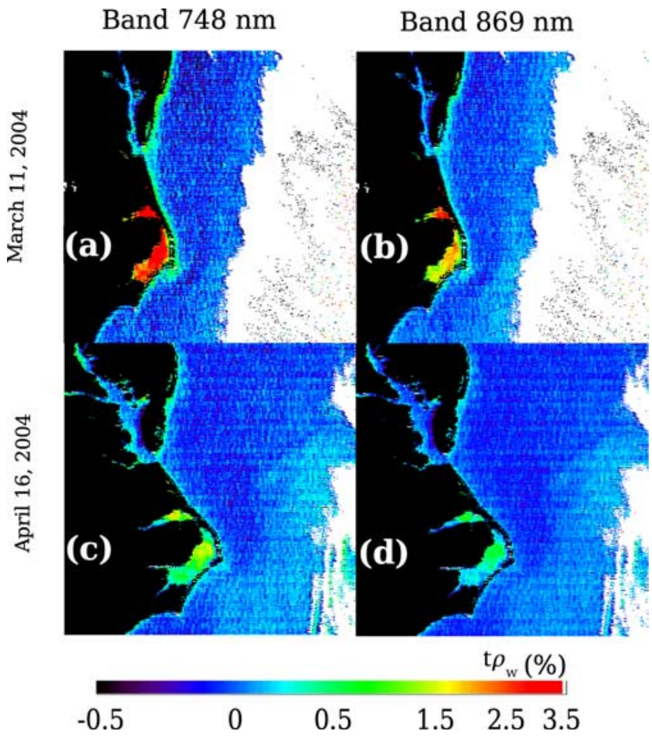

Figure 3. The MODIS-derived images in the TOA water-leaving reflectance from the east coast of US for (a) and (b) on March 11, 2004 at wavelength 748 and 869 nm, respectively, and (c) and (d) on April 16, 2004 at wavelength 748 and 869 nm, respectively.

4. Results

[12] We choose two granules from MODIS Terra measurements, which were acquired on March 11, 2004 (file 20040711515) and April 16, 2004 (file 20041071625), with clear atmosphere in the region of the east coast of the U.S. to derive the TOA ocean contributions for the MODIS NIR bands. Figure 3 provides color images in the MODIS derived ocean reflectance $t\rho_w(\lambda)$ at 748 and 869 nm for the U.S. east coast region. Figures 3a and 3b are results of $t\rho_w(\lambda)$ corresponding to the wavelength at 748 and 869 nm for case of March 11, 2004, while Figures 3c and 3d are results for case of April 16, 2004. The value of $t\rho_w(\lambda)$ in the image is scaled from −0.5%–3.5% and indicated in the color bar. The derived negative $t\rho_w(\lambda)$ values that usually occur in the open ocean are due mainly to the sensor noises. Clearly, in the coastal regions, there are significant ocean contributions in the NIR. These are particularly apparent in the Chesapeake Bay and Outer Banks regions. The temporal variation in the NIR ocean contributions is also obvious. For the region of the Outer Banks, $t\rho_w(\lambda)$ values can reach as high as ∼3.1% and ∼1.8% at the wavelengths 748 and 869 nm, respectively, on March 11, 2004, while they are ∼0.5% and ∼0.3% on April 16, 2004. These ocean NIR contributions are very significant. In fact, such bright signals at the NIR for the case of the Outer Banks are often mistakenly masked as clouds when the reflectance threshold at 869 nm is used for cloud detection.

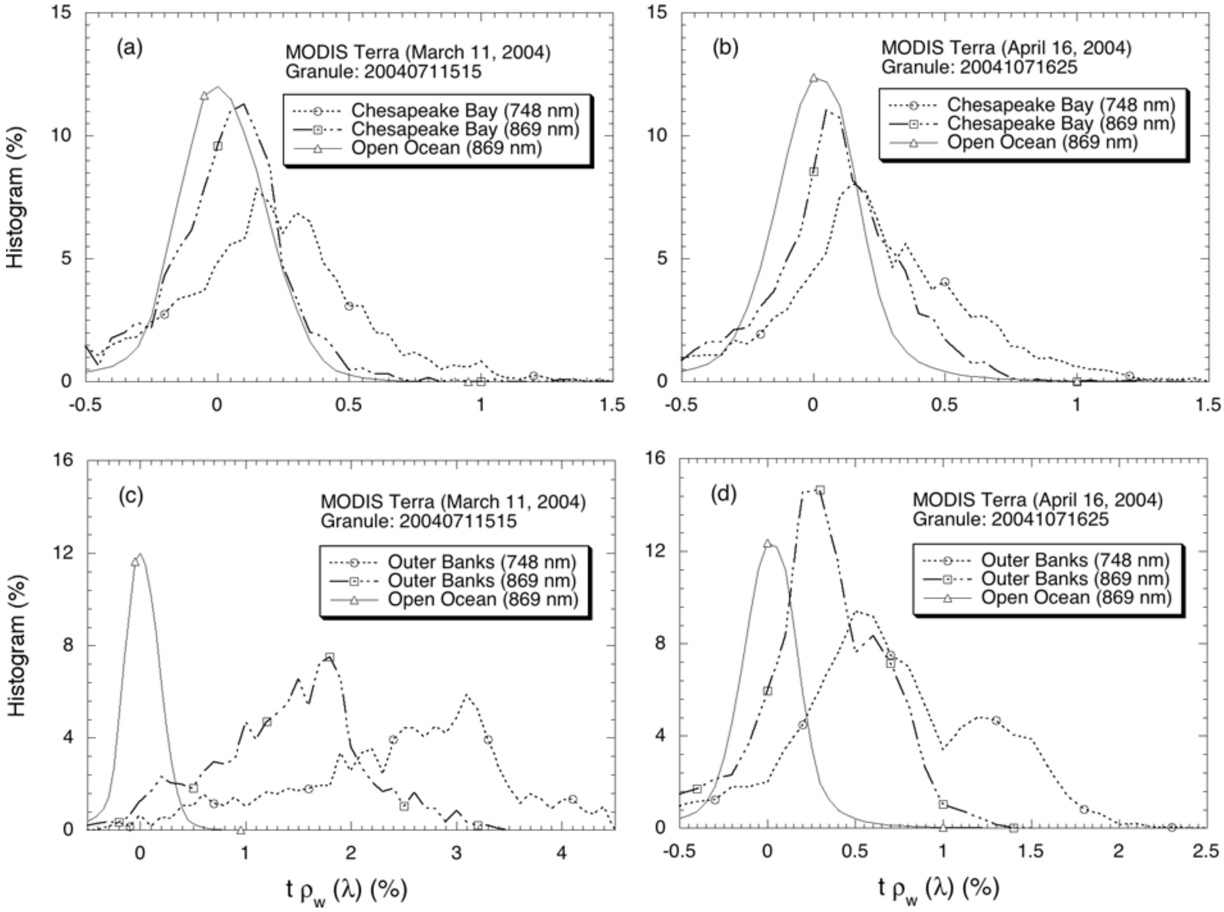

Figure 4. Comparison of the histograms in the MODIS-retrieved TOA water-leaving reflectance at the NIR bands for (a) and (b) from Chesapeake Bay on March 11 and April 16, 2004, respectively, and (c) and (d) from Outer Banks on March 11 and April 16, 2004, respectively. The open ocean results at 869 nm are also provided.

[13] Figure 4 provides the histogram of the derived TOA water-leaving reflectance $t\rho_w(\lambda)$ at the MODIS two NIR bands from ocean regions of the Chesapeake Bay and Outer Banks as presented in Figure 3. Figures 4a and 4b are histogram results in the derived NIR $t\rho_w(\lambda)$ from the Chesapeake Bay region, while Figures 4c and 4d are derived from the Outer Banks. These results are from the MODIS data acquired on March 11, 2004 (Figures 4a and 4c) and April 16, 2004 (Figures 4b and 4d) in the U.S. east coast region. For comparison, each plot in Figure 4 includes $t\rho_w(\lambda)$ at 869 nm derived from open ocean in the same scene (Figure 3). We also obtained similar results at 748 nm from the open ocean. The NIR open ocean results in $t\rho_w(\lambda)$ verify that the ocean is indeed black for the clear Case-1 waters. This also verifies the correctness of the data processing procedure. Both the Chesapeake Bay and Outer Banks show significant ocean contributions for the NIR bands. In particular, we note that the Outer Banks has extremely large $t\rho_w(\lambda)$. The mode values in $t\rho_w(\lambda)$ are 3.1% and 1.8% at 748 and 869 nm for March 11 case, while they are peaked at 0.5% and 0.3% for the case of April 16, 2004. We found that the spectral distribution of the ocean contribution in the Outer Banks for case of Figure 4c is very similar to the sediment-dominated water, peaked at the green-red range (results are not shown here). The Chesapeake Bay has also non-negligible $t\rho_w(\lambda)$ values at the NIR. The mode values are ~0.15% and ~0.1% at 748 and 869 nm for both cases in Figures 4a and 4b.

[14] Clearly, significant $t\rho_w(\lambda)$ contributions for the NIR bands in the Chesapeake Bay and Outer Banks regions need to be accurately accounted for in the MODIS atmospheric correction for the ocean color products [*Gordon and Wang*, 1994] and for retrieval of aerosol optical properties [*Wang et al.*, 2005]. Without accounting for the NIR ocean contributions, derived water-leaving reflectance $\rho_w(\lambda)$ at the visible will be biased low, while the aerosol reflectance $\rho_A(\lambda)$ will be over-estimated (aerosol optical thickness will be biased high). In other words, the ocean contributions at NIR bands are mistakenly accounted as coming from aerosol contributions, leading to over-subtraction of the aerosol reflectance in the visible and thus under-estimation of the $\rho_w(\lambda)$ values (see equation (2)).

5. Summary

[15] Using the MODIS measurements in the SWIR bands, we demonstrate that the TOA ocean contributions at the NIR wavelengths can be derived. In the SWIR, the ocean is usually black even for the turbid waters due to much stronger water absorption. Thus, the MODIS-measured SWIR data are useful for evaluating aerosol contributions and for atmospheric correction for ocean color

products in the coastal regions. Using such an approach for deriving the ocean color products for the coastal regions, a bio-optical model that estimates the ocean contributions in the NIR bands is not needed.

[16] **Acknowledgment.** This research was supported by the NASA NPP and MODIS grants NNG04GE05A and NNG04HZ22C.

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